BNL-91101-2010-CP

FFAG Designs for the International Design Study for the Neutrino Factory

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Presented at the 23rd Particle Accelerator Conference
Vancouver, B.C., Canada
May 4-8, 2009

February 2010

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DISCLAIMER

FFAG DESIGNS FOR THE INTERNATIONAL DESIGN STUDY FOR THE NEUTRINO FACTORY

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Abstract

The International Design Study for the Neutrino Factory (IDS-NF) aims to produce a design report for a neutrino factory. One component of that design is a linear non-scaling fixed-field alternating gradient accelerator (FFAG) that will accelerate to the final energy of 25 GeV. An FFAG is used to reduce the machine cost by maximizing the number of passes made through the RF cavities. We present some design options for this FFAG, individually optimized for cost. We study the addition of nonlinear magnets to the lattice to improve the performance of the lattice and consider the negative effects of doing so.

PURPOSE OF THE FFAG

The International Design Study for the Neutrino Factory (IDS-NF) [1] is a collaboration which aims to produce a reference design report for a neutrino factory by the year 2012, with an intermediate design report in 2010. One function of the neutrino factory complex which will be detailed in these design reports will be to accelerate muons to 25 GeV total energy. The cost of the acceleration in the machine increases with the amount of RF voltage in the machine. We would therefore like to maximize the number of passes that the bunches make through the RF cavities.

The most straightforward way to have more than one pass through the RF cavities is to construct a recirculating linear accelerator (RLA), wherein multiple passes are made through a single linac. After each pass through the linac, the bunches are returned back to the linac through an arc (assuming they are not extracted to the next stage). For each pass, the bunches pass through a different arc.

It is difficult to make a large number of passes through the linac in an RLA due to the switchyard which guides the beam into the separate arcs. The nonzero energy spread in the beam, finite beam size, and nonzero space required for magnet coils and other hardware effectively limit the number of passes to 4 or 5. The number of passes can also be limited by the inability to maintain focusing in the linac over a wide energy range [2].

To avoid the switchyard and achieve a larger number of passes through the RF cavities, one can instead use a fixed-field alternating gradient accelerator (FFAG). Such a machine has a single arc with an energy acceptance covering the full range of the machine. A linear non-scaling FFAG is used due to its relatively small apertures and the fact that the machine can be made isochronous near the center of its energy range, enabling the use of high-frequency RF (201.25 MHz) whose frequency cannot be changed during the acceleration cycle [3].

In this paper, we will first describe a starting design for the linear non-scaling FFAG. We will then motivate and describe the chromaticity correction of the design.

LINEAR NON-SCALING FFAG DESIGN

The FFAG should accelerate from 12.6 GeV to 25 GeV total energy. It should have an normalized transverse acceptance of 30 mm and a normalized longitudinal acceptance of 150 mm. The design of the FFAG will be optimized using the techniques described in [4, 5]. We present 5 different designs. Their cell structure will be FODO, double, and triplet, with one or two cavity cells per lattice cell. We consider multiple designs at this stage to allow the consideration of both efficiency and the ease of injection and extraction in choosing an optimal configuration. With a single cavity, a doublet lattice has a modest cost advantage over other designs [4]. However, since we wish to accelerate both signs of muons, and since injection and extraction become significantly easier if the magnet adjacent to the septum is defocusing in the plane of injection/extraction, there are advantages to the FODO and triplet designs.

If one only considers cost, it is generally an advantage to leave a number of cells without cavities in a muon acceleration FFAG. However, the longitudinal dynamics in an FFAG is disturbed by the dependence of the time of flight on the transverse amplitude [6]. This effect is reduced by increasing the average accelerating gradient [6, 7]. Therefore in all of our designs, the number of cells occupied by RF cavities is maximized; the cost penalty for doing so is less than 4% [8]. We thus consider designs with a single RF cell in every cavity cell that is not occupied by other hardware (in our case for injection and extraction). The FODO cell in this configuration is highly inefficient and will thus not be considered. In addition, to further reduce the effect, we consider designs with two RF cells per lattice cell.

Drifts containing one cavity cell are 2 m long, and drifts containing two cavity cells are 3 m long. This ensures that fields from the magnets are reduced below 0.1 T by the time they reach the cavity walls. 50 cm is left between adjacent magnets. Magnets will be combined-function rectangular magnets with dipole and quadrupole field components.

The resulting optimized configurations are given in Tab. 1. There is a cost penalty for having multiple RF cavity cells per lattice cell. The reason for this is that if one had the same number of cavity cells but used two cavity cells

* Work Supported by the United States Department of Energy, Contract No. DE-AC02-98CH10886.

Configuration	FDC	FDFC	FCDC	FDCC	FDFCC
Cells	77	70	62	62	55
D length (m)	1.132860	1.484148	1.255079	1.292983	1.978298
D shift (mm)	23.775	27.500	43.393	34.937	41.049
D field (T)	5.976713	5.333164	6.126946	6.468864	5.244332
D gradient (T/m)	-27.164458	-26.243837	-15.752554	-18.125261	-1.6367255
F length (m)	1.894483	1.020626	2.196536	2.744577	1.305721
F shift (mm)	-4.985	4.277	-1.998	-5.742	9.251
F field (T)	-1.081587	-1.180637	-0.838980	-0.866284	-1.188423
F gradient (T/m)	20.893314	24.952793	12.202411	11.199120	16.356841
Cavity cells	71	64	120	112	98
RF voltage (MV)	902.962	813.937	1526.132	1424.390	1246.341
turns	14.6	16.2	8.7	9.3	10.6
D radius (mm)	77	92	95	102	125
D max field (T)	8.1	7.7	7.6	8.3	7.3
F radius (mm)	140	122	207	203	167
F max field (T)	4.0	4.2	3.4	3.1	3.9
Circumference (m)	426	422	462	467	445
Decay (%)	5.4	5.9	3.5	3.8	4.1
Cost (A.U.)	133.9	143.8	176.4	174.8	180.6

Table 1: Optimized linear non-scaling FFAG lattice designs.

per lattice cell, the ring circumference would be shorter while the lattice cell lengths increased, and the larger fields and apertures required actually increase the magnet cost despite the reduction in the number of magnets [5].

CHROMATICITY CORRECTION

Due to the time of flight dependence on transverse amplitude, the longitudinal dynamics of particles with different transverse amplitudes will differ, giving an effective longitudinal emittance growth [6]. This is especially important for muon beams due to their large transverse amplitude. This effect results from the nonzero chromaticity in FFAG lattices [7]. Thus, to reduce the effect, we would like to reduce the chromaticity of the lattice. The potential problem with this is a reduction in dynamic aperture.

In order to reduce the chromaticity, we introduce multipole components to the magnets, and adjust those multipole components to minimize the sum

$$\sum_k [(\nu_{xk} - \nu_{x0})^2 + (\nu_{yk} - \nu_{y0})^2] \tag{1}$$

where the index k refers to the energy at which the tune is computed, and iterates from 12.5 GeV through 25.0 GeV in 2.5 GeV steps. The subscript 0 refers to the tune at 22.5 GeV.

The corrected tune is shown in Fig. 1. There is little benefit in including components beyond sextupole. Fig. 2 shows that the dynamic aperture is reduced significantly when adding multipole components above the sextupole order. Thus we only use sextupoles.

There is a performance cost of this chromaticity correction: the magnet apertures are increased and the time of flight becomes an asymmetric function of energy. These increase the cost and reduce the number of turns one will be able to make in the lattice.

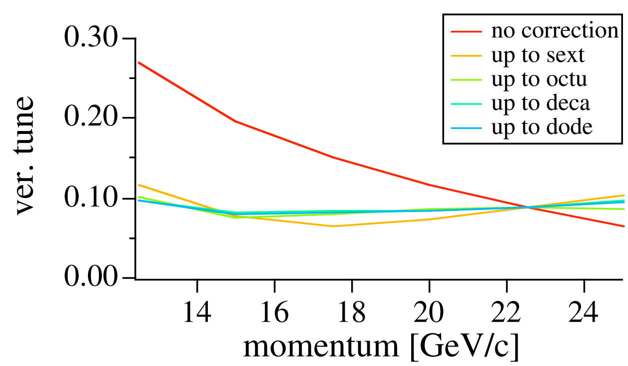

Figure 1: Vertical tune per cell as a function of energy for the chromatically corrected lattice with various numbers of multipole components used. Similar behavior is seen in the horizontal plane.

With the chromaticity correction computed as above, the dynamic aperture is close to (FCDC) or lower than (FDFCC) the 30 mm desired for muon acceleration. However, if one reduces the sextupole strength, one partially corrects the chromaticity (reducing the time of flight dependence on transverse amplitude) while improving the dynamic aperture. The dynamic aperture as a function of the sextupole strength is shown in Fig. 3. It appears to rise to acceptable levels when the sextupole strengths are reduced to 70% of their chromaticity-correcting values. It however dips lower when the sextupole strength is reduced further (this appears to be caused by the $3\nu_x = 1$ resonance, and may therefore be possible to avoid). The dynamic apertures are not much above the required value of 30 mm, however,

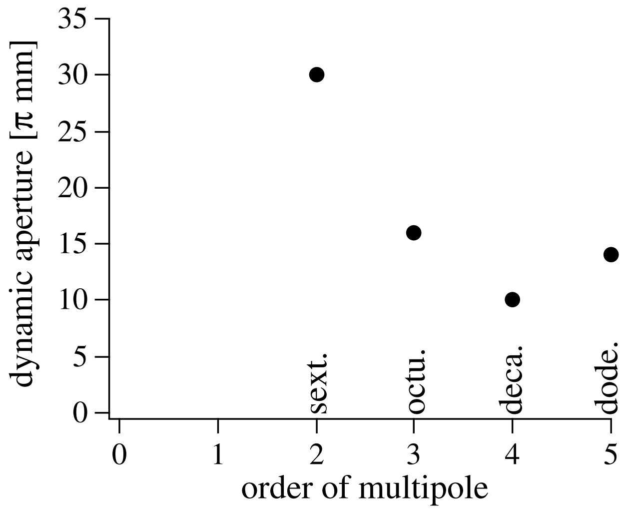

Figure 2: Dynamic aperture (FCDC) as a function of the number of multipole components used to chromatically correct the lattice. Dynamic aperture is computed by accelerating by 20 MeV per cell from 12.6 GeV to 25 GeV.

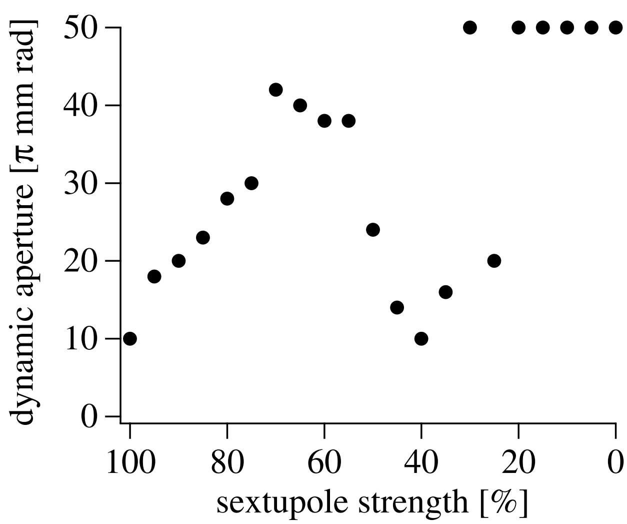

Figure 3: Dynamic aperture (FDFCC) as a function of sextupole strength. 30 mm is desired for muon acceleration. Dynamic apertures plotted as 50 mm may be higher.

and we are therefore concerned whether they will still be that high when errors are included. However, it appears that at least some small level of chromaticity correction will be possible.

We have also studied adding cells with longer drifts into the lattice to ease the requirements on the kicker magnets. This breaks the symmetry of the lattice, potentially causing significant orbit distortions and emittance growth [9]. Without chromaticity correction, it was impossible to insert such cells. However, with even partial chromaticity correction (at the 70% level), it was possible to add cells with 7 m drifts with minimal reduction in dynamic aperture.

NEXT STEPS

Initial results from the design for injection and extraction [10] indicate that for the FODO lattice, at least 6 drifts are needed for kickers. If one shared sets of injection kickers and extraction kickers, the 4 septa required would require 16 drifts without RF cavities. Furthermore, we have decided that 4 drifts should be empty to accommodate other hardware. The number of lattice cells will be a multiple of four to allow for superperiodicity to reduce the driving of resonances due to different magnets that may be required in the injection and extraction regions. New lattices will be designed which meet these constraints.

It appears that in the injection and extraction regions, the beam cannot be contained in the magnet apertures given above. Due to the cost, it is not desirable to have large aperture magnets everywhere, and we would therefore like to confine such magnets to the injection and extraction regions. This will break the symmetry of the lattice which is critical for the performance of FFAG lattices [9]. We must thus study the magnet parameters which will reduce the driving of resonances due to this symmetry breaking.

We need to continue studying what level of chromaticity correction we can add to the lattice and still maintain an acceptable level of dynamic aperture, even when errors are included. We must study the effects of this chromaticity correction on the cost and performance of the machine. We must also determine whether it will be possible to ease injection and extraction kicker requirements by adding cells with longer drifts for those systems.

Finally, detailed tracking studies, including the effects of errors, must be performed on the lattice to verify the performance of a complete system.

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